# Impact of Proton Irradiation on the Static and Dynamic Characteristics of High-Voltage 4H-SiC JBS Switching Diodes

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*Abstract*—**The effects of proton irradiation on the static ($dc$) and dynamic (switching) performance of high-voltage 4H-SiC Junction Barrier Schottky Diodes (JBS) are investigated for the first time. In contrast to that observed on a high-voltage Si $p-i-n$ diode control device, these SiC JBS devices show an increase (degradation) in series resistance ($R_S$), a decrease (improvement) of reverse leakage current, and increase (improvement) in blocking voltage after high-fluence proton exposure. Measured breakdown voltages of post-irradiated SiC diodes increase on average by about 200 V after irradiation. Dynamic reverse recovery transient measurements shows good agreement between the various $dc$ observations regarding differences between high-power SiC and Si diodes, and show that SiC JBS diodes are very effective in minimizing switching losses for high-power applications, even under high levels of radiation exposure.**

## I. Introduction

Silicon carbide (SiC) is a promising candidate for high-power and high-frequency applications because of its wide bandgap (>3 eV) and excellent thermal/electrical properties [1]. SiC-based devices are very attractive for military and space-based power electronics systems because of their fast switching speeds compared to Si, their low switching losses, and their ability to operate in extreme environments such as high temperature (e.g., to 500C) and/or under high levels of radiation. The radiation literature on SiC devices is very limited, and studies to date have been centered on terrestrial detector systems. 4H-SiC neutron detectors, for instance, have been demonstrated with no significant degradation of detection efficiency after neutron fluences up to $1x10^{17} n/cm^2$ [2]. Devices based on 6H-SiC have shown negligible degradation of device characteristics for gamma radiation doses up to 100 Mrad, but showed significant degradation with neutron irradiation for fluences in excess of $1x10^{16} n/cm^2$ [3], [4].

In earlier studies, the effects of high-dose gamma irradiation on unterminated 4H-SiC Schottky diodes and the $SiC-SiO_2$ interface was examined [5], and no observable degradation in the diode forward and reverse characteristics up to a total dose of 4 Mrad(Si) was observed. Measured breakdown voltages of post-irradiated diodes increased, however, approximately 200 V compared after irradiation, and was attributed to increased negative interface charge. In the present work, we present for the first time the effects of proton irradiation on both the $dc$ and $ac$ characteristics of terminated 4H-SiC high-voltage JBS power switching diodes. JBS diodes have been shown to have great promise for power switching systems, since they effectively balance the best properties of both Schottky Barrier Diodes (SBD) (high speed) with $pn$ junction diodes (low leakage currents and hence losses). A comparison is made to commercially-available high-voltage Si $p-i-n$ power diodes in order to better understand the results.

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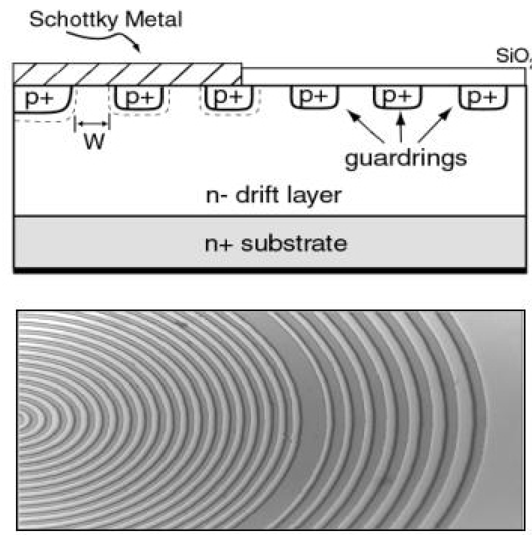


Fig. 1. SiC JBS structure with floating guard ring edge termination.

## II. Experiment

Circular SBD and JBS diodes with diameters ranging from $100\mu$m to $400\mu$m were fabricated at Auburn University on 4H-SiC n+ wafers having a $30\mu$m thick $1x10^{15} cm^{-3}$ n- epitaxial layer grown at Cree, Inc. The active JBS regions, together with the floating guard ring structures needed for proper edge termination, were formed using Al (i.e., p-type) implantation at high temperatures. The guard rings as well as $p^+$ implants used in forming the JBS active region were $5\mu$m in width, while the JBS ring-to-ring spacing ($W$) varied from $3\mu$m to $5\mu$m. Al implants were annealed at 1600 °C, as has been described in the literature [6]. The guard ring-to-guard ring spacing and number for a given device design was chosen after extensive calibrated quasi-3D simulations to optimize the breakdown properties of the device in question. A high quality thermal oxide followed by a $1\mu$m poly-Si layer, which was then converted to oxide, was used for surface passivation. Ni was deposited for the backside ohmic contacts and annealed at 1100 °C for 2 minutes in vacuum, followed by evaporation of Ti and Au for decreased contact resistance. Schottky contact openings were formed by selective RIE followed by a BOE etch through the passivation and immediate loading into the metalization chamber for Ni schottky contact evaporation. Schottky contacts were completed with Ti and Au overlayers. A schematic cross section and top-down photograph of the fabricated diodes is shown in Fig. 1.

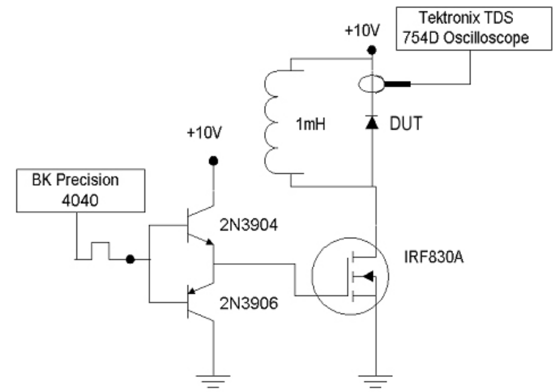


Fig. 2. Schematic of the test circuit used in the reverse recovery transient measurements.

Proton irradiation of the SiC SBD, SiC JBS, and the packaged commercial Si $p-i-n$ control diode (UF1007) was performed at the Crocker Nuclear Laboratory Cyclotron Facility located at the University of California at Davis, using 62.5MeV protons, to a total fluence of $5x10^{13}p/cm^2$, with terminals floating. Both *dc* and *ac* characteristics were measured and compared for both SiC diodes and Si diodes before and after radiation exposure. The low-voltage forward and reverse current-voltage characteristics were measured using an Aglient 4155 Semiconductor Parameter Analyzer. Reverse breakdown measurements were performed using a Tektronix 371 high voltage curve tracer. For reverse recovery measurements, the inductive switching test circuit shown in Fig. 2 was used. In this test circuit, the device-under-test (DUT) is connected as a "freewheeling" diode in parallel with an inductive load. This circuit is designed to provide a $dI_r/dt$ of -10A/$\mu$sec.

## III. Results and Discussion

### A. dc Characteristics

Fig. 3 shows typical forward *dc* characteristics of a JBS diode with 3 $\mu$m JBS ring spacing and 7 guard ring termination, both before and after $5x10^{13}p/cm^2$ irradiation. As is widely known, adequate edge termination is critical in power devices in order to minimize field crowding at the device edges and hence maximize breakdown voltage [7]. The termination structure used here employs multiple floating guard ring structures carefully optimized via calibrated simulations, and has proven to be very effective at providing sufficient termination without enhancing processing complexity [8].

The low-injection region of the $J-V$ curve shows little change after irradiation, suggesting that proton exposure does not degrade the Schottky contact of the device (i.e., the barrier remains unchanged at 0.94 eV). In addition, however, the forward voltage drop clearly increases at higher currents due to proton-induced series resistance. The series resistance ($R_s$) increases dramatically in the case of the JBS diode shown, from 25Ω (pre-rad) to

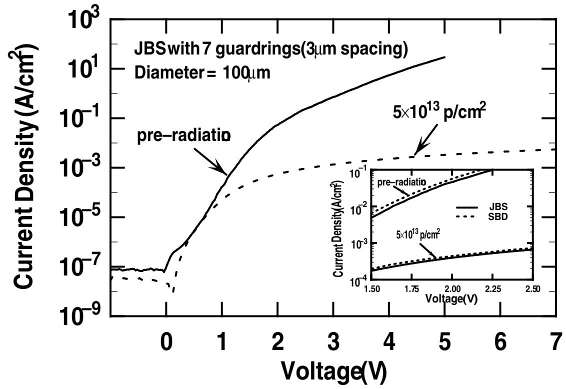


Fig. 3. Forward current-voltage characteristics of the 7 guard ring terminated 4H-SiC JBS diode, before and after proton exposure. Inset:enlarged J-V characteristics of the 7 guard ring terminated 4H-SiC JBS and SBD diodes (100 $\mu$m diameter), before and after proton exposure

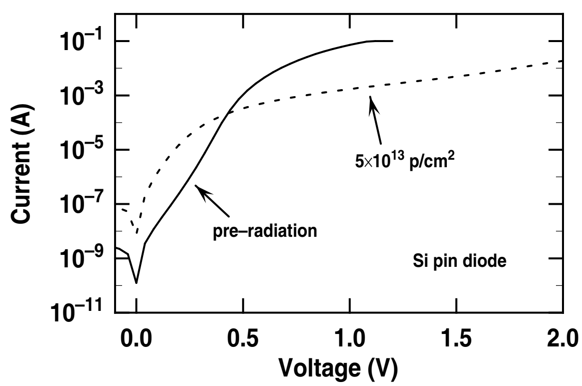


Fig. 4. Forward current-voltage characteristics of the Si $p-i-n$ diode before and after proton exposure.

12.1MΩ (post-rad). This result is surprising, given that previous research showed little or no degradation of $R_s$ after gamma radiation, even up to 100 Mrad total dose, and suggests that SiC device behavior depends strongly on the radiation type. Our results are repeatable, however, across many devices on separate samples, indicating that the effect is real. The source of the added resistance after irradiation is either due to: 1) added contact resistance from the metal itself, 2) a decrease in doping level due to displacement effects, or 3) a radiation-induced change in the carrier mobility, or a combination of the three. In order to eliminate potential contact resistance changes, we remeasured the J-V characteristics of the JBS diode using a Kelvin contact (force bias on one probe and measure on the other probe) in order to eliminate contact resistance, obtaining in this case $R_s$=7.2MΩ. This suggest that proton exposure has changes the surface chemistry of the metal, consistent with our earlier experience on SiGe HBTs, but it does not explain the net resistance change. Clearly displacement damage can also de-ionize dopant impurities and/or introduce traps into SiC, thereby leading to an increase in series resistance from the bulk of the wafer [9], [10], [11]. From the $C-V$ measurements on the SBD, we obtained $2-5x10^{14}cm^{-3}$ epi effective doping level, down from a starting value of $1-2x10^{15}cm^{-3}$ in the active region of the device (i.e., reverse bias can only probe a finite volume of the wafer. This suggests that proton-induced dopant de-ionization also plays a role in the resistance increase after proton exposure.

The inset of Fig. 3 is the enlarged portion of the $J-V$ characteristics of the same JBS diode from 1.5V to 2.5V, comparing to a standard terminated SBD diode. Both SBD and JBS diodes present similar forward-mode performance, before and after radiation, suggesting that the *pn* junction inherent to the JBS stucture are not responsbile for the observed resistance changes. For comparison to these SiC results, Fig. 4 shows the $I-V$ characteristics of the commercial Si $p-i-n$ diode (area and type of termination structure are unknown). The Si $p-i-n$ diode shows much stronger degradation in the low-bias region, consistent with G/R center production and lifetime changes in the device epi region. Interestingly, we also see a significant series resistance increase after proton exposure, presumably also due to dopant de-ionization.

A very surprising result is that we consisently observe a *decrease* in the reverse current of the SiC diodes after radiation (Fig. 5), which is opposite to the (expected) degradation observed in the Si diode (Fig. 6). The reverse current density of the SiC diodes decreases from $1.6x10^{-7}A/cm^2$ to $7x10^{-8}A/cm^2$ at 10V. For Si diodes, on the other hand, the current dramatically increases from $6.8x10^{-9}A$ to $1.4x10^{-7}A$ at 10V, consistent with radiation-induced G/R center production and hence lifetime reduction. For the SiC, this result is actually consistent with an earlier report using $EBIC$ which indicated that electron irradiation can have a pronounced annealing effect on carrier lifetime in 6H-SiC epi [14], although this has not been observed to our knowledge using protons. This reverse leakage current result is also interesting, in that it would appear to be inconsistent with the observed series resistance increase due (at least partially) to dopant de-ionization. To explain both sets of data requires a damage mechanism which can simultaneously de-ionize dopant impurities and increase the carrier lifetime. We are continuing to investigate this further.

We have observed that the breakdown voltage actually increases in these SiC JBS diodes after proton exposure, one of the few instances when radiation actually *improves* device characteristics.For Si pin diode, breakdown voltage has no obvious change and remains around 1300V. Fig. 7 shows the radiation-induced change in breakdown voltage as a function of number of guard rings used in the termination structure in SiC diodes. The average increase in breakdown voltage is 220V, a significant improvement. Clearly, the effect is not strongly dependent on the number of rings, although a gradual saturating trend at high guard ring count is apparent. A peak blocking voltage in this technology is 1780V after $5x10^{13}p/cm^2$ exposure.

We have previously observed a similar breakdown voltage increase in unterminated SiC SBD diodes after gamma radiation and attributed that to an increase of negative surface charge in the $SiO_2$/SiC passivation layer [5], [15]. A negative surface charge increases the depletion layer spreading, thus reducing the effects of field crowding at the device edge, thereby increasing the breakdown voltage. Given the similar observed trends to the blocking voltage, a similar explanation is certainly plausible here, even though the radiation type is different. In addition, we note that the dopant de-ionization needed to explain the series resistance increase would also improve the breakdown voltage,

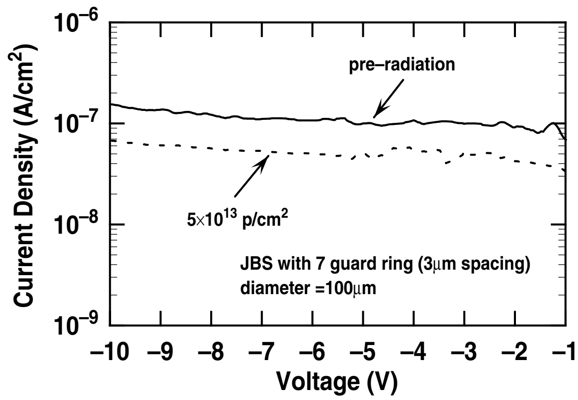


Fig. 5. Reverse current-voltage characteristics of the terminated 4H-SiC JBS diode before and after proton exposure.

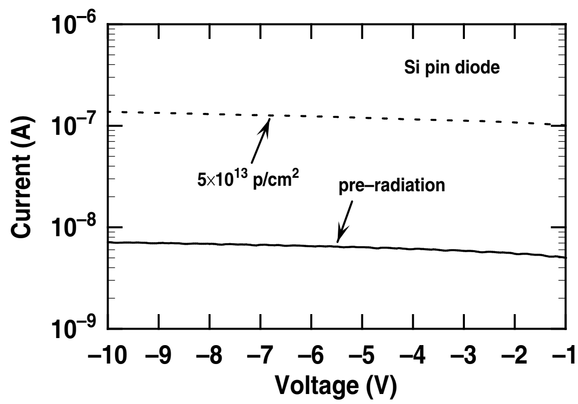


Fig. 6. Reverse current-voltage characteristics of the Si $p-i-n$ diode before and after proton exposure.

and thus it is likely that a combination of both effects in operative here. Using calibrated MEDICI simulations [16], the breakdown voltage for the planar diode structure was calculated for both surface charge changes as well as doping level changes. The simulation results suggest that a doping change from $1x10^{15}cm^{-3}$ to $7x10^{14}cm^{-3}$ would cause a 200V breakdown increase, while a negative charge change increase from $-1.67x10^{-12}cm^{-2}$ to $-3.24.x10^{-12}cm^{-2}$ would cause a similar increase. Further experiments involving proton exposure of MOS capacitors will be needed to sort this out, and is underway.

### B. Switching Characteristics

SiC JBS diodes have a negligible reverse recovery current compare to Si $p-i-n$ diode, greatly improving their losses for high-power switching circuits (Fig. 8 ). In the Si $p-i-n$ structure, the observed reverse recovery current is primarily due to minority carrier storage (set by the carrier lifetime). The JBS diode, however, is a majority carrier device (like the SBD), and hence has negligible carrier storage under high-injection currents. As shown in Fig. 9 for pre-radiation, the Si $p-i-n$ diode has a reverse recovery current peak ($I_{rr,max}$) of 930mA and reverse recovery time ($t_{rr}$) of 101ns, while for the SiC JBS diode, $I_{rr,max}$ is only 62mA and with a $t_{rr}$ of 38ns.

After radiation, the Si $p-i-n$ diode yields a significantly decreased reverse recovery current, as shown in Fig. 9. Both

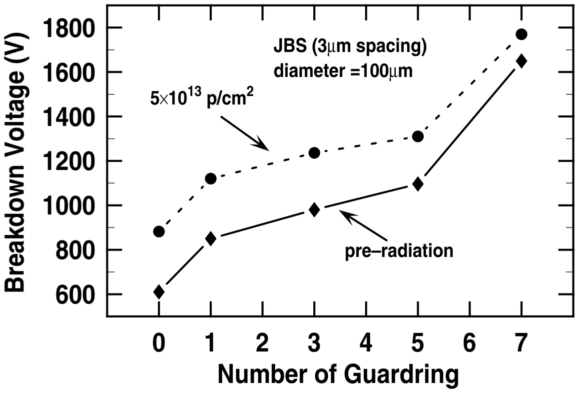


Fig. 7. Comparison of measured breakdown voltage of the JBS diode between pre- and post-irradiation as a function of number of guard rings used in the edge termination.

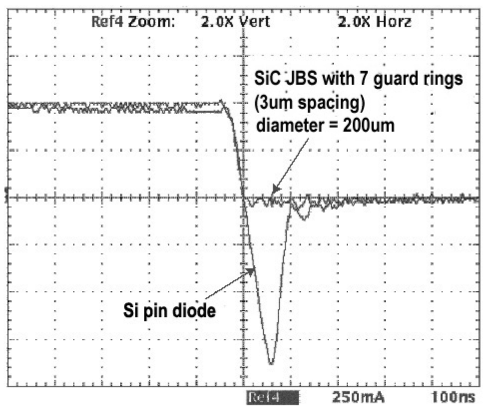


Fig. 8. Reverse recovery transient waveforms comparing the SiC JBS and Si $p-i-n$ diodes.

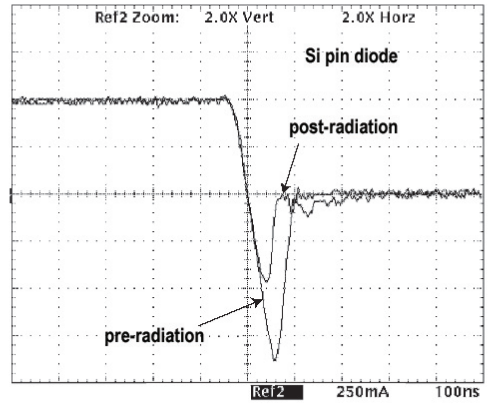


Fig. 9. Reverse recovery transient waveforms comparing the pre- and post-irradiated Si $p-i-n$ diode.

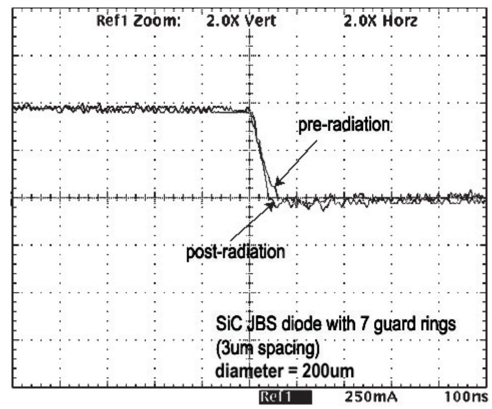


Fig. 10. Reverse recovery transient waveforms comparing the pre- and post-irradiated SiC JBS diode.

$I_{rr,max}$ and $t_{rr}$ dramatically decrease from 930mA and 101ns to 480mA and 69ns. This indicates the minority lifetime strongly decreases after proton exposure, consistent with our reverse leakage current observations. Similarly, electron radiation has been shown to strongly decrease the carrier lifetime in Si power devices [17]. As expected, for the SiC diodes, there is little change after irradiation, although we do still see a similar trend of increased $I_{rr,max}$ and $t_{rr}$ with proton exposure. For the particular terminated SiC JBS diode shown in Fig. 10, $I_{rr,max}$ remains the same at 62mA while $t_{rr}$ increased from 38ns to 44ns after proton exposure. These reverse recovery transient measurements are obviously low-voltage measurements, and more detailed *ac* characterization at higher $di_{rr}/dt$, and at full blocking voltage will need to be made, and is underway.

## IV. Summary

The effects of proton irradiation on the static and dynamic performance of high-voltage 4H-SiC JBS diodes have been investigated for the first time. In contrast to that observed on a high-voltage Si $p-i-n$ diode control device, these SiC JBS devices show an increase (degradation) in series resistance, a decrease (improvement) of reverse leakage current, and increase (improvement) in blocking voltage after high-fluence proton exposure. Dynamic reverse recovery transient measurements shows good agreement between the various *dc* observations regarding differences between high-power SiC and Si diodes, and show that SiC JBS diodes are very effective in minimizing switching losses for high-power applications, even under high levels of radiation exposure.

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